Exclusive charmed meson pair production

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The experimental data of BELLE Collaboration on the exclusive charmed meson pair production in the process of monophotonic e^+e^--annihilation ($e^+e^- \to \gamma^* \to D\bar{D}$) has been studied. It has been shown that these data is described satisfactorily in the frame work of constituent quark model. Our studies have demonstrated that the central production process $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-D\bar{D}+X$ and the process of monophotonic e^+e^--annihilation yield comparable numbers of the charmed meson pairs.

1. INTRODUCTION

The exclusive meson pair production is the unique opportunity to research the asymptotic behaviour of the meson form factor in the frame work of pQCD. The heavy meson pair production is of special interest. In this case the effective heavy quark theory allow us to connect the meson production processes with the meson decay processes [1]. The asymptotic form factor behaviour is described by the factorized amplitude which can be represented as a wave function $f(x,Q)$ multiplied by a hard interaction amplitude [2]. In the leading order of α_s only one gluon exchange contribute into the hard interaction amplitude and the wave function $f(x,Q)$ have peak at $x = \Lambda_{QCD}/M$, where Λ_{QCD} is a strong interaction scale, and M is heavy quark mass. The distribution of $f(x,Q)$ over x becomes thiner with increasing heavy quark mass. Due to this feature one can use the following approximation for the wave function:

$$f(x,Q) \sim \delta\left(x - \frac{m_q}{M}\right). \qquad (1)$$

In this approach the momentum fraction carried out by quark is proportional to the quark

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mass:

$$x_i \simeq \frac{m_i}{M}.$$

The models of such kind [2] are taking into account the hard "tail" of the wave function only and neglect the soft component of the wave function. Nevertheless these models correctly reproduce the cross section behaviour near the threshould as well as asymptotic behaviour at $Q^2 \to \infty$. Moreover, difference between the peak approximation calculation and the calculation beyond the peak approximation (1) is not essential [3]. In this work we endeavour to study the recent experimental results of BELLE collaboration [4] for $D^{*+}D^{*-}$-pair production in e^+e^--annihilation at $\sqrt{s} = 10.6$ GeV. Also we predict the cross section value of the charmed meson pair production in $\gamma\gamma$-interaction at BELLE.

2. E^+E^--ANNIHILATION

The following cross section values of the charmed meson pair production in e^+e^--annihilation have been measured by BELLE Collaboration[4]:

$$\sigma(e^+e^- \to D^{*+}D^{*-}) = 0.65 \pm 0.04 \pm 0.07 \text{ pb},$$

$$\sigma(e^+e^- \to D^{+}D^{*-}) = 0.71 \pm 0.05 \pm 0.09 \text{ pb}.$$

The differential cross section distributions over azimuthal angle have been measured too.

The interaction energy at BELLE (10.6 GeV) is large enough to determinate the leading asymptotic contribution into the meson form factor:

$$F(Q^2) \simeq \frac{\alpha_s f_M^2}{Q^2},$$

where f_M is the constant of leptonic decay, and $Q^2 = s = (k_{e^+} + k_{e^-})^2$ is the e^+e^--interaction energy squared. Nevertheless, it is worth to mention that the virtuality of gluon splited into quark-antiquark pair $q\bar{q}$ is slightly smaller than this energy

$$q^2 \sim x_q^2 Q^2,$$

where x_q is the momentum fraction of the meson carried out by the light quark (See Fig. 1). If the pre-asymptotic terms would be large, then the model prediction would not reliable. But as it was shown in paper [3], the pre-asymptotic terms are not essential.

Let us return to the discussion of the constituent quark model. As it mentioned above, the cross section behaviour near the threshould is described correctly by this model: $\sigma \sim \left(\frac{s}{4} - M^2\right)^{(2L+1)/2}$,

where L is orbital momentum of the meson pair. (For production in e^+e^--annihilation $L = 1$.) At $M \to \infty$ the constituent quark model, as well as the effective theory of heavy quarks give the same predictions for the cross section ratio:

$$\sigma_{PP} : \sigma_{PV} : \sigma_{VV} = 1 : 4 : 7,$$

where P and V are pseudoscalar state and vector state, correspondingly [5]. At large energy the cross sections σ_{PP}, σ_{PV} and σ_{VV} behave as follows:

$$\sigma \sim \frac{\alpha^2 \alpha_s^2}{s^3}.$$

An angular distribution of the cross sections have the following simple form:

$$\frac{d\sigma(D\bar{D})}{d\cos\Theta} \sim \sin^2\Theta,$$

$$\frac{d\sigma(D\bar{D}^*)}{d\cos\Theta} \sim 1 + \cos^2\Theta,$$

where Θ is the angle between the final meson direction and the initial beam direction in the center-of-mass system.

For the case of $D\bar{D}^*$ pair production only transversal component of D^* contributes into cross section, because the production of longitudinal D^* component do not allowed by lows of parity and angular momentum conservation. Indeed, in the center-of-mass system the matrix element of $D\bar{D}^*$ production in 1^- state looks like follows:

$$[\epsilon_{\mathbf{D}^*}(\mathbf{p}) \times \mathbf{p}] \cdot \epsilon_{\mathbf{q}} \varphi_D,$$

where $\epsilon_{\mathbf{D}^*}$ and $\epsilon_{\mathbf{q}}$ are polarizations of D^* and virtual photon, correspondingly. One can see from this formula, that the longitudinal component contribution D^*

$$\epsilon_{\|} = \mathbf{n}(\mathbf{n}\epsilon_{D^*})\frac{E}{m},$$

equals to zero ($\mathbf{n} = \mathbf{p}/|\mathbf{p}|$, E and M are energy and mass of D^* meson).

The longitudinally polarized D^* meson could be produced in the process of diphotonic e^+e^--annihilation, but as is was shown in [6], the charmed meson yield is small for this process.

The pair production of vector mesons D^* and $\bar{D}^*$ in the center-of-mass system can be describe by two independent structures:

$$M_1 \sim (\epsilon_{\mathbf{1}}\mathbf{p})(\epsilon_{\mathbf{2}}\epsilon_{\mathbf{q}}) + (\epsilon_{\mathbf{2}}\mathbf{p})(\epsilon_{\mathbf{1}}\epsilon_{\mathbf{q}}),$$

$$M_2 \sim (\epsilon_{\mathbf{1}}\epsilon_{\mathbf{2}})(\mathbf{p}\epsilon_{\mathbf{q}}).$$

Both amplitudes correspond to 1^- state of the dimeson system. First amplitude contribute to $D^*_L D^*_T$-pair production. Second one contribute to all possible variants of particle polarizations. The ratio between these amplitudes depends on the quark masses.

The satisfactory description of the experimental data of BELLE Collaboration has been achieved for the following values of the model parameters:

$$\alpha_s = 0.3,$$

$$f_D = 200 \text{ MeV},$$

$$m_q = 0.17 \text{ GeV},$$

$$m_c = 1.5 \text{ GeV}.$$

We have predicted the following cross section values:

$$\sigma(D^{*+}D^{*-}) : \sigma(D^+D^{*-}) : \sigma(D^+D^-) = 0.73 \text{ pb} : 0.58 \text{ pb} : 0.02 \text{ pb}$$

One can see that the production of two pseudoscalar mesons is suppressed by the order of magnitude.

The experimental angular cross section distribution $d\sigma/d\cos\Theta$ for the processes of $D^*\bar{D}^*$- and $D\bar{D}^*$-pair production in comparison with the model predictions has been shown in Fig. 2. The best description of the experimental data is achieved for $m_q = 0.17$ GeV and $m_c = 1.5$ GeV.

It is worth to mention that the model under discussion is rather rough approach, which takes into account only hard "tail" of the meson wave function. The contribution of the soft part of wave function has been neglected. That is why the cross section dependence on energy have not minimum for the case of production of the two pseudocalar mesons, which has been predicted in the frame work of the effective theory of heavy quarks [1]. However cross section values predicted in [1] are large than experimental data by the order of magnitude. It is worth to mention ones more, that the results of calculations above the peak approximation (1) do not differ essentially from the results obtained in the frame work of peak approximation [3].

3. PHOTONIC PRODUCTION OF $D^{(*)}\bar{D}^{(*)}$-PAIR

The exclusive production of $D^{(*)}\bar{D}^{(*)}$-pair in the photon-photon interaction has been studied in our paper [7]. Our results have been compared with the predictions of the effective theory of

heavy quarks. In the constituent quark approach the photonic production of the charmed meson pair is described by twenty Feynman tree level diagrams (see Fig. 3). The analogous diagram set has been used to calculate the inclusive B_c-meson production cross section [8]. This diagram set can be subdivided into three gauge invariant parts. The first group of diagrams (1-6 of Fig. 3) corresponds to the case when heavy quark radiates gluon which splits into light quark pair. The second group (diagrams 7-12) can be received from the first one by permutation $Q \leftrightarrow q$. The third diagram group (diagrams 13-20 of Fig. 3) corresponds to the independent production of the of the quark pairs ($\gamma \to QQ$, $\gamma \to q\bar{q}$) followed by there fusion into mesons.

The third diagram group dominates at relatively small transverse momenta. Due to the contribution of such diagrams the factorization theorem can not be applied to describe the inclusive production of B_c-meson in the wide kinematic region [8]. In particular, the strong cross section dependence on light quark charge e_q exists near the threshould as well as at large interaction energy. Also, we have observed such e_q dependence for the process of photonic $D^{(*)}\bar{D}^{(*)}$ pair production. That process feature has underlined also in the paper [9] for the region of large energies.

In this article we continue our study of the constituent quark model prediction for different kinematic regions. Our analysis is based on diagrams of Fig. 3.

Let us consider the $D^{(*)}\bar{D}^{(*)}$ pair production near the threshould. As it has been mentioned above, $D^*\bar{D}^*$ pairs and $D\bar{D}$ ones are produced near the threshould in S-wave state. (The cross section depends on momentum k between D-mesons in the center-of-mass system as $\sim k^{2L+1}$). This state corresponds to the total momentum and parity of the diphoton system 0^+. On the contrary, $D^*\bar{D}$-pair is produced in P-wave, because S-wave state production is not allowed by the Landau-Yang theorem.

S-wave state of the meson pair is produced from the $\gamma\gamma$ system 1^+. P-wave state of the meson pair $D^*\bar{D}$ corresponds to the $\gamma\gamma$ system 0^-, thus the cross section of the $D^*\bar{D}$ production increases near threshold as k^3. As one can see in Fig. 4, the cross section values of $D^{(*)}\bar{D}^{(*)}$-pair production depend on light quark charge, whereas quantum numbers of the meson pair, as well as energy behaviour of the cross sections do not depend on this charge value. Also, one can see, that the cross section distribution over angle for neutral meson pair and charged meson pair differ from each other considerably.

Our model predicts practically isotropic production of the $D^0\bar{D}^0$-, $D^{*0}\bar{D}^0$-, $D^0\bar{D}^{*0}$-, D^+D^-- and $D^{*+}D^{*-}$-pairs near the threshould:

$$\frac{d\sigma}{d\cos\Theta} \approx const,$$

whereas D^+D^{*-}-pair produce peripherally even near the threshould (see Fig. 5). However, as it can be clearly seen in Fig. 4, the production of such pairs is suppressed near the threshould. It is worth to mention, that the total cross section value of the neutral meson production is three times large than the cross section value of the charged meson production.

At large energies the cross section distributions over $\cos\Theta$ have peripheral form with striking maxima at +1 and -1. This fact has been also emphasized in the paper [9], where the analytic form of amplitude of the pseudocalar meson pair production has been performed at hight energy limit:

$$A^{\rm PP} \sim \left[(e_Q - e_q)^2 \frac{1+\beta^2\cos\Theta^2}{1-\beta^2\cos\Theta^2} + 2e_Q^2 \right],$$

where

$$\beta = \sqrt{1-\frac{4m^2}{s}}.$$

At large value of s one can see the difference between the asymptotic behaviour of the cross sections for the charged and neutral meson production. The production cross section depends on s as $1/s^2$ for all charged meson pair. On the contrary, the production cross sections for neutral meson pairs have different asymptotes:

$$\sigma_{D^0\bar{D}^0} : \sigma_{D^{*0}\bar{D}^0} : \sigma_{D^{*0}\bar{D}^{*0}} \sim \frac{1}{s^3} : \frac{1}{s^4} : \frac{1}{s^2}.$$

However, it is worth to mention that the cross section behaviour becomes asymptotic after $\sqrt{s} > 20$ GeV, therefore the study of it have the theoretical importance only. In addition, the next order logarithmic corrections can play essential role at such energies.

4. $D^{(*)}\bar{D}^{(*)}$-PAIR PRODUCTION IN $\gamma\gamma$-INTERACTION AT BELLE

It has been shown in the paper [6] that the contribution of diphotonic annihilation

$$e^+e^- \to \gamma^*\gamma^* \to D\bar{D} \tag{2}$$

into the total cross section is small.

Nevertheless, another opportunity to produce charmed meson pairs in the photon-photon interaction exists. Charmed mesons could be produced in the interaction between the effective (equivalent) photons radiated by the initial fermions:

$$e^+e^- \to e^+\gamma e^-\gamma \to D\bar{D} + e^+ + e^-. \tag{3}$$

The cross section of this process is described in the frame work of the "partonic" model:

$$\sigma = \int\int \sigma_{\gamma\gamma}(\hat{s}) f^{\gamma}(x_1) f^{\gamma}(x_2) dx_1 dx_2,$$

where x_1 and x_2 are momentum fractions of the initial electron and positron, correspondingly, carried out by interacting photons. The photonic density $f^{\gamma}(x)$ obeys Weizëcker-Williams formula:

$$f^{\gamma}(x) = \frac{\alpha_{\rm em}}{2\pi x}\left(\left(1-(1-x)^2\right)\ln\frac{Q^2_{\rm max}}{Q^2_{\rm min}} - m_e^2 x^2\left(\frac{1}{Q_{\rm min}} - \frac{1}{Q_{\rm max}}\right)\right),$$

where m_e is the mass of electron, $Q^2_{\rm min} = m_e^2 x^2/(1-x)$, and $Q^2_{\rm max} \simeq 1$ GeV^2.

In contrast to the diphotonic annihilation (2) the amplitude of process (3) is not suppressed by s-canal propagators. Thus it would be interesting to estimate the cross section value for the process of the charmed meson production in the interaction between the effective photons.

For the parameter values used to estimate the cross section in e^+e^--annihilation we have received the following unexpected results for the process (3):

$$\sigma(D^{*+}D^{*-}) : \sigma(D^{+}D^{*-}) : \sigma(D^{+}D^{-}) = 1.52 \text{ pb} : 0.33 \text{ pb} : 0.13 \text{ pb}.$$

$$\sigma(D^{*0}\bar{D}^{*0}) : \sigma(D^{0}\bar{D}^{*0}) : \sigma(D^{0}\bar{D}^{0}) = 1.39 \text{ pb} : 0.43 \text{ pb} : 0.40 \text{ pb}.$$

It is clear that these cross section values are comparable with ones for the process of e^+e^--annihilation. One can see in Fig. 6, that the distribution shapes do not differ essentially from ones for the case of e^+e^--annihilation. It is obvious, that the meson energy is less than the energy of meson produced in e^+e^--annihilation. The distribution over $z = \frac{2|\mathbf{p_D}|}{\sqrt{s}}$ is shown in Fig. 7, where $\mathbf{p_D}$ is the D meson momentum in the center-of-mass system of e^+e^--pair. One can see from that distribution that the averaged value of z is about 0.3 for the such process. Therefore the averaged meson momentum is about 1 GeV.

It is worth to notice that the model under discussion predicts the dominance of the vector-vector pair production.

CONCLUSION

We have shown that the experimental data on charmed meson pair production at BELLE ($\sqrt{s} = 10.6$ GeV) is described satisfactorily in the frame work of the constituent quark model. In that approach the hard part of the amplitude can be calculated with the help of pQCD motivated diagrams.

The production mechanism in e^+e^--annihilation is rather simple. The virtual photon splits into $c\bar{c}$-pair followed by hardonization process. Thus the cross section value do not depend on light quark charge.

In contrast to e^+e^--annihilation in $\gamma\gamma$-interaction the cross section values depends strongly on the light quark charge at low energy, as well as at high energy. The essence of matter is that in the process $\gamma\gamma \to D\bar{D}$ the light quark interaction with the photonic field can not be neglected.

It has been shown that the cross section value of the central D meson production in the process

$$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-D\bar{D} + X$$

and the cross section value of D meson production in e^+e^--annihilation are comparable.

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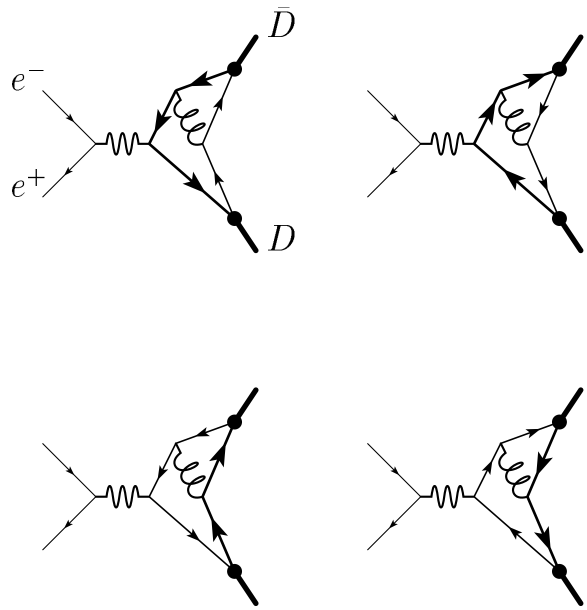

Figure 1. Feynman diagrams for the process of charmed meson pair production in e^-e^+-annihilation.

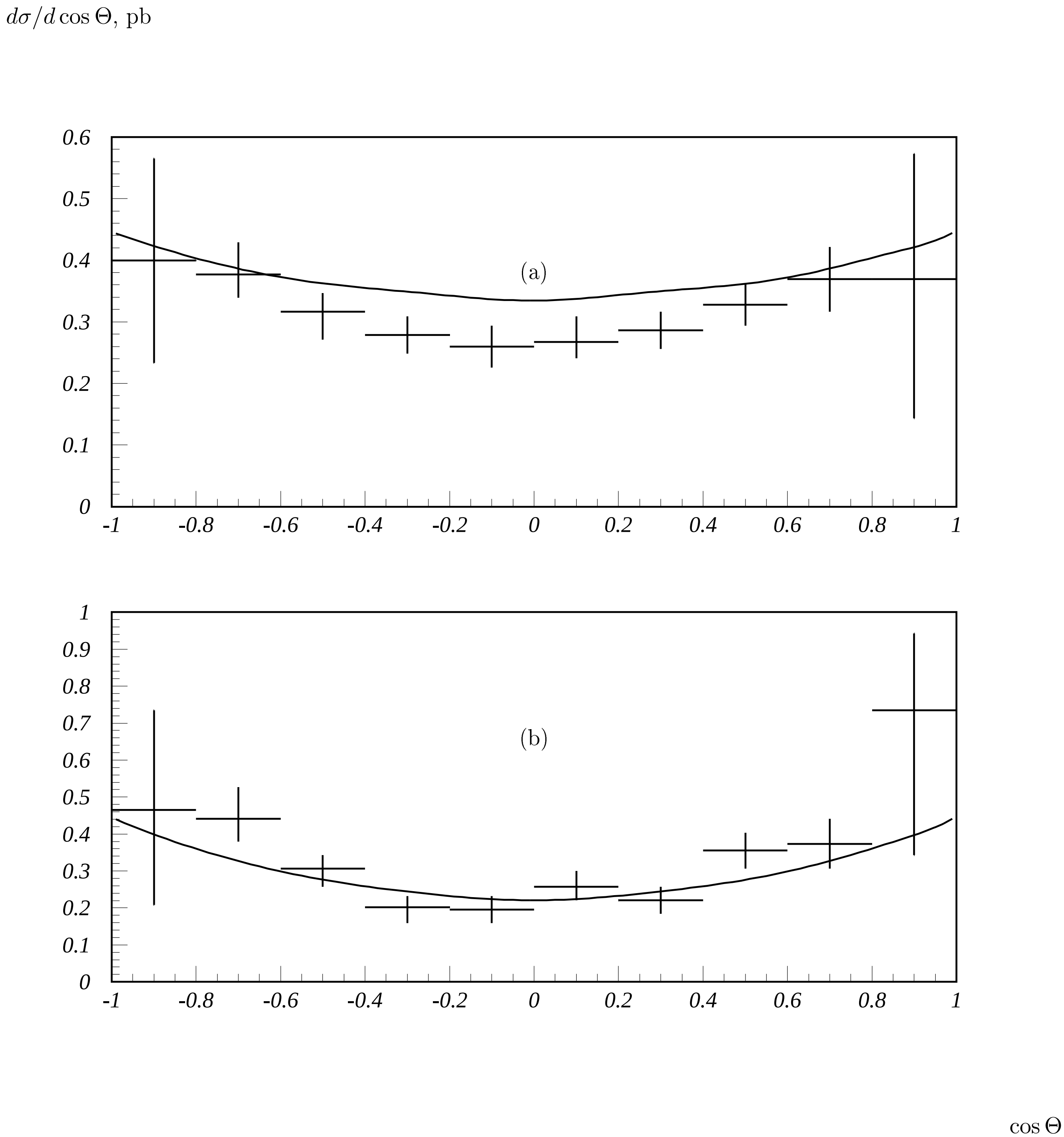

Figure 2. The cross section distribution over $\cos\Theta$ (pb) in comparison with the experimental data for the process $e^+e^- \to D^*\bar{D}^*$ (a) and for the process $e^+e^- \to D^*\bar{D}$ (b). $m_c = 1.5$ GeV, $m_q = 0.17$ GeV, $f_D = 200$ MeV, $\alpha_s = 0.3$.

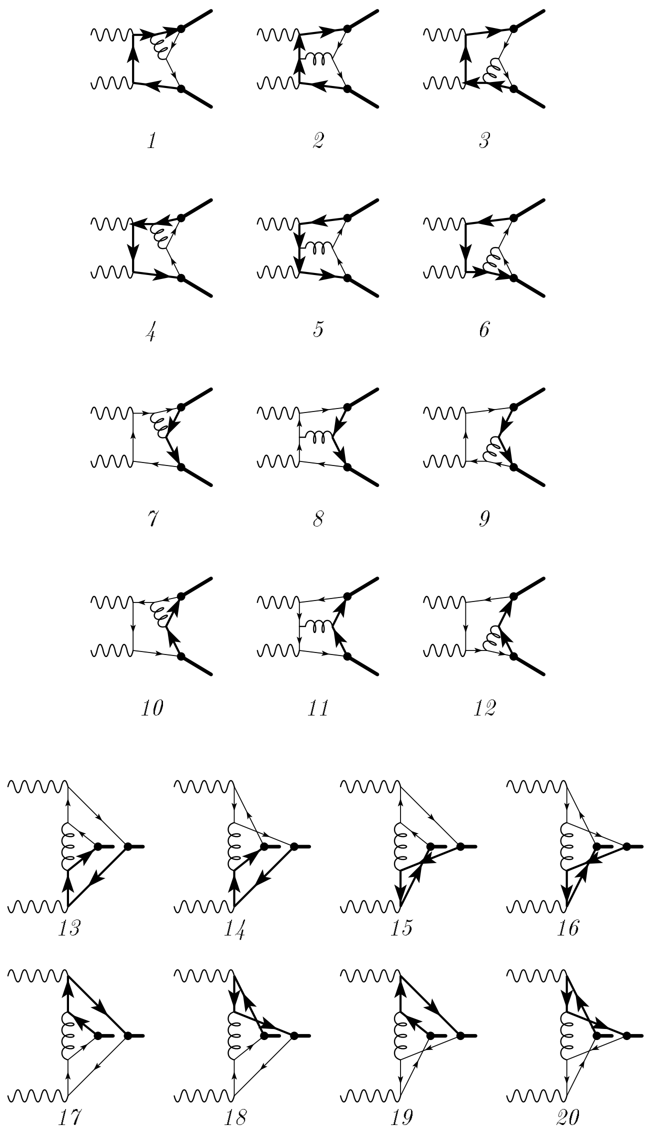

Figure 3. Feynman diagrams for the charmed meson pair production in the photon-photon interaction.

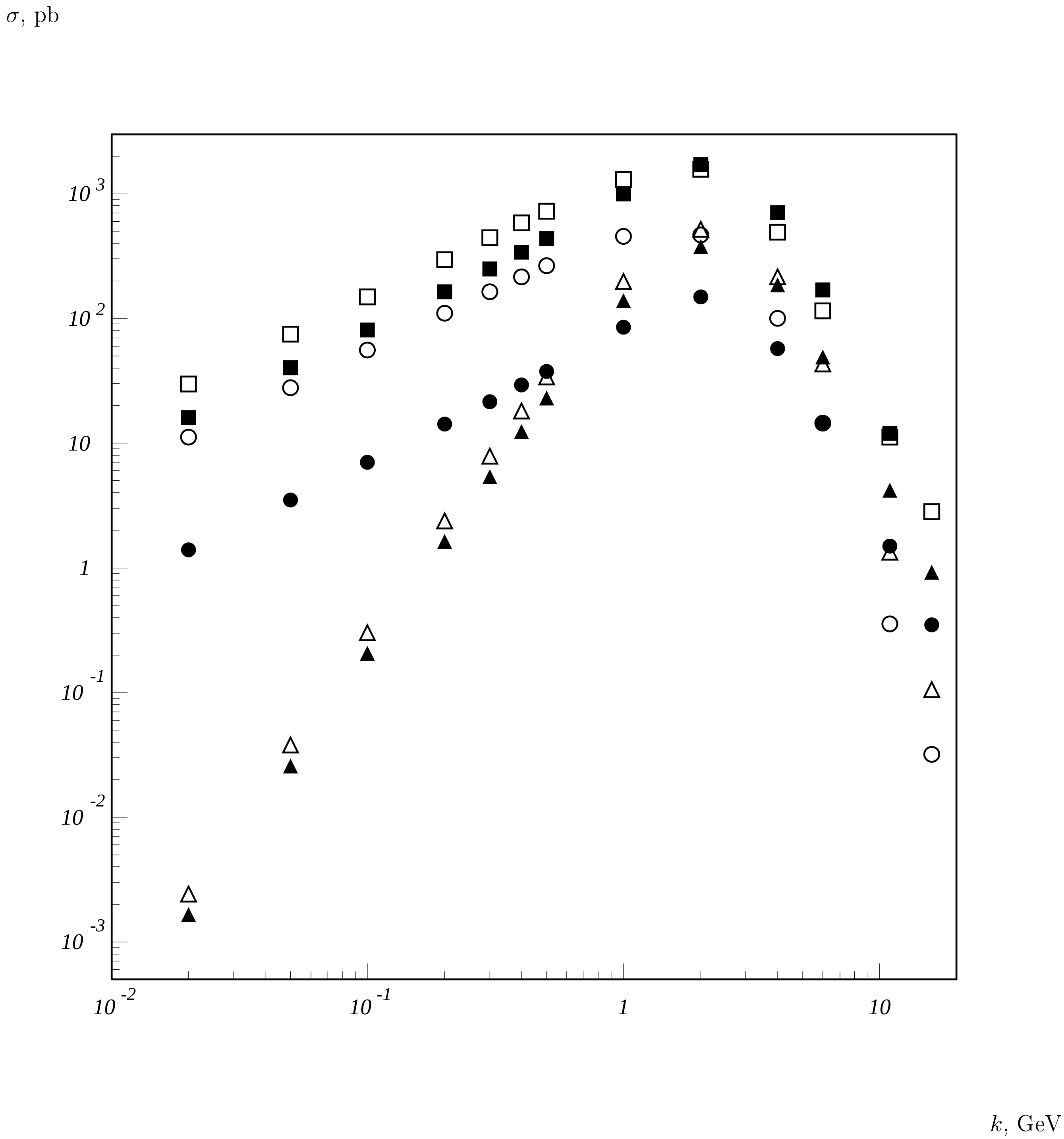

Figure 4. The cross sections σ_{PP} ($\circ$, $\bullet$), σ_{PV} ($\triangle$, $\blacktriangle$), σ_{VV} ($\square$, $\blacksquare$) as a function of $k = \sqrt{s - s_{th}}$ for neutral D-mesons (closed symbols) and for charged D-mesons (opened symbols).

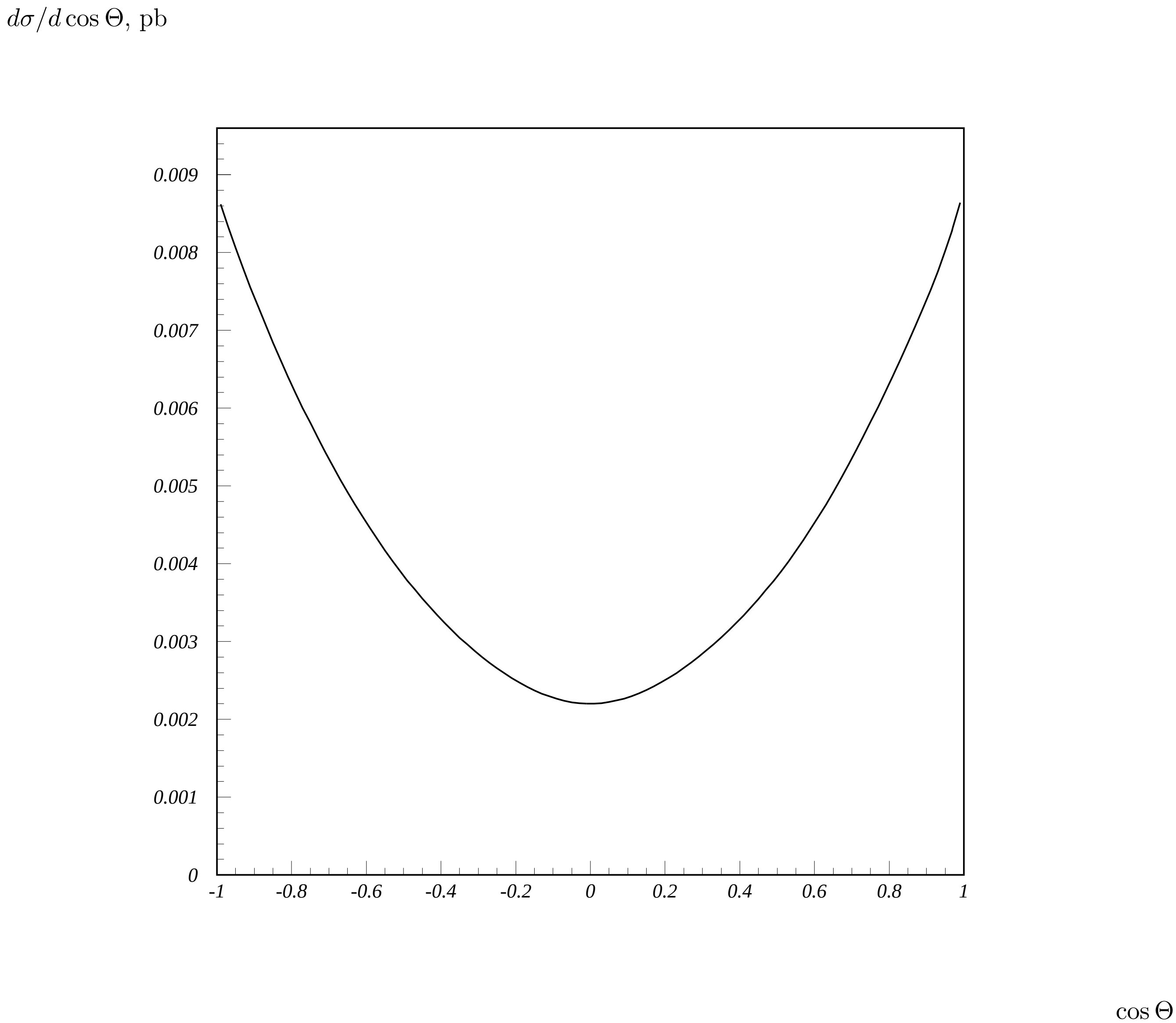

Figure 5. The cross section distribution over $\cos\Theta$ for the processes of D^+D^{*-} and D^-D^{*+} pair production in the Ч e^+e^--annihilation at $k = \sqrt{s - s_{th}} = 0.1$ GeV. (Other meson pairs are produced at small k isotropically.)

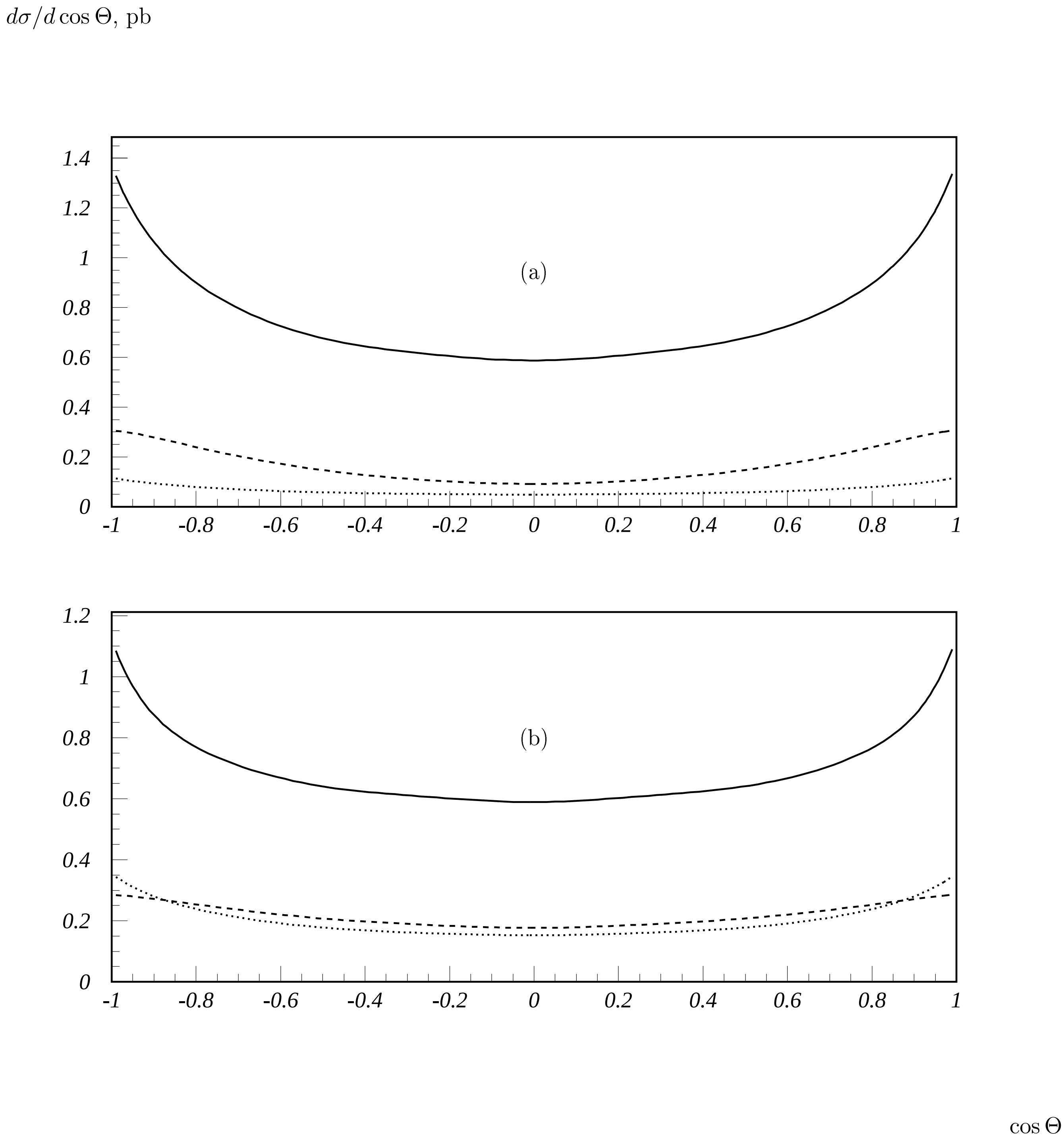

Figure 6. The differential cross section $d\sigma_{VV}/d\cos\Theta$ (solid curve), $d\sigma_{PV}/d\cos\Theta$ (dashed curve) and $d\sigma_{PP}/d\cos\Theta$ (dotted curve) for the processes of charged meson production (a) and neutral meson production in the effective photons interaction.

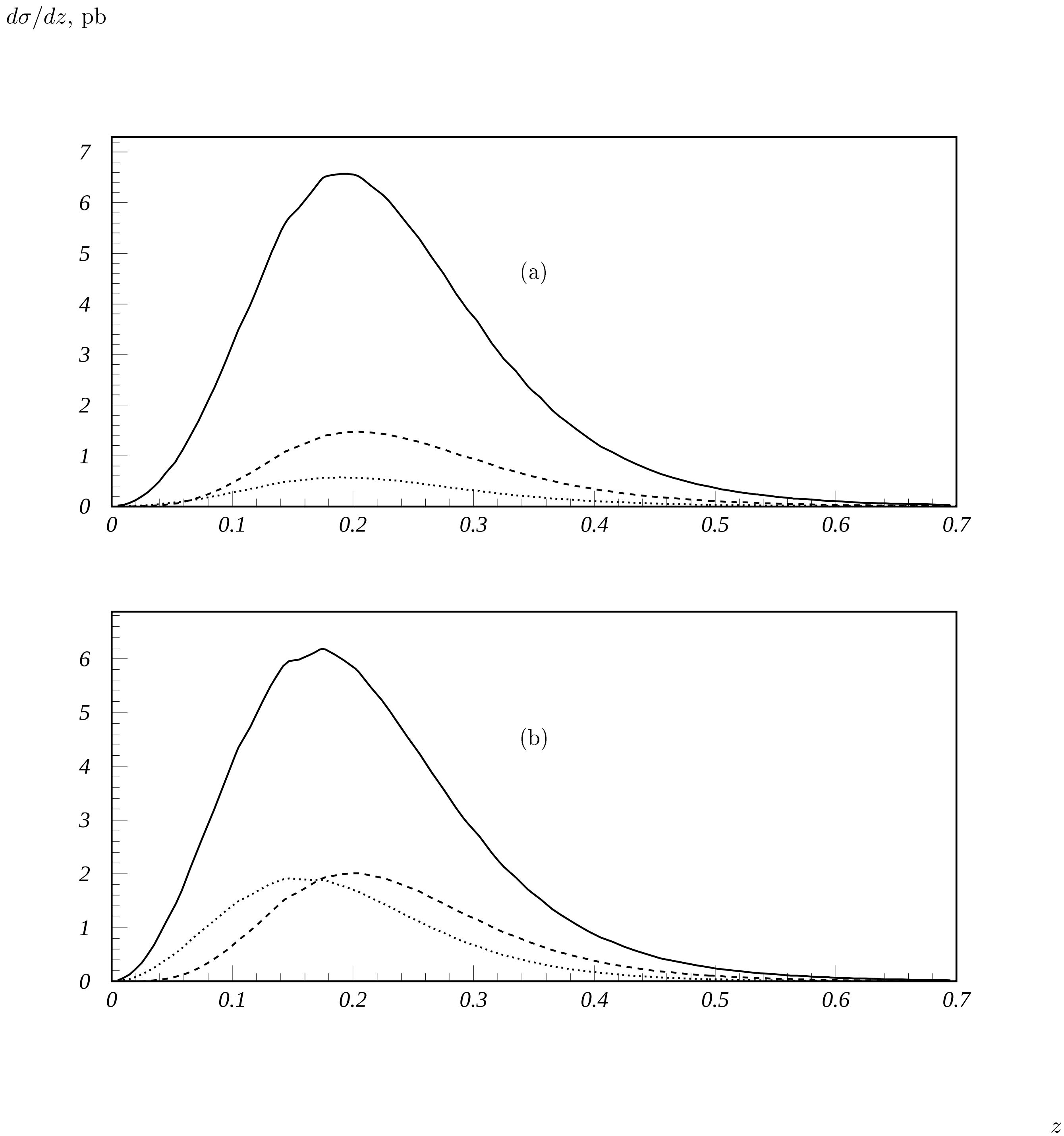

Figure 7. The cross section distributions over $z = \frac{2|\mathbf{p_D}|}{\sqrt{s}}$ for the processes of charged meson production (a) and neutral meson production (b) in the effective photon interaction. The designations are the same as in Fig. 6.